Assessment of coronary artery bypass grafts patency with different magnetic resonance technologies

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Abstract

Objective: The aim of the study was to evaluate the diagnostic accuracy of different magnetic resonance (MR) sequences in the assessment of coronary artery bypass graft patency and the evaluation of distal anastomoses with a spin echo sequence (Haste).

Patients and methods: Twenty-five patients were examined with all the three techniques and 185 patients with 481 distal anastomoses were examined with the Haste sequence at a 1.5 TMR scanner and coronary angiography. A two-dimensional T2-weighted breath-hold half-Fourier acquisition single-shot turbo spin echo sequence (Haste), a Navigator sequence and a gadolinium-enhanced Fisp-3-D sequence were performed. All images were evaluated independently by a radiologist and cardiologist and compared to the conventional coronary angiography. The observers were blinded to the coronary angiography findings, but informed in regard to the surgical graft anastomosis.

Results: With the Haste sequence 80% of the distal anastomoses were recognized. The sensitivity and specificity for the evaluation of the distal anastomosis with the Haste sequence was 94% and 75%. The Navigator and the Fisp-3-D sequences showed a sensitivity of 74% and 94% and a specificity of 78% and 88%.

Conclusion: The best results were achieved with the Haste sequence, a reliable assessment of graft patency of the distal anastomosis is possible. The best imaging of proximal IMA segments was possible with the Fisp-3-D sequence. Due to the low sensitivity and specificity, the use of the Navigator sequence was stopped in our center. Further improvements of the spatial resolution and the image quality are necessary to recommend this MR techniques for routine clinical use.

Keywords: Coronary artery bypass grafts; Haste sequence; Magnetic resonance imaging

1. Introduction

Myocardial ischemia induced by coronary artery disease (CAD) represents the most common cause of premature death in western countries [1]. The therapy of CAD aims to maintain myocardial blood flow using interventional procedures or coronary artery bypass grafting (CABG). Surgical myocardial revascularization is performed to improve the myocardial function and appears to be associated with a long-term improvement in quality of life [2]. Late symptoms and clinical outcome after CABG are mainly dependent on the status of the bypass grafts [3,4]. In the first five years after CABG, the occlusion rate of saphenous vein grafts is up to 20%, therefore only 5% of the internal mammary grafts are occluded after this time [5,6]. At present, the gold standard for the assessment of graft patency is coronary angiography. In clinical practice, the method has several disadvantages. The procedure is invasive, there is a need for significant ionizing radiation and there is extensive use of contrast agent.

Magnetic resonance imaging (MRI) potentially meets the requirements of a noninvasive follow-up procedure for CABG patients. The technique is widely available and can be performed on an outpatient basis without any X-ray exposition. Several authors have investigated time-of-flight (TOF) and phase contrast (PC) magnetic resonance angiography (MRA) as means of assessing CABG [7]. As a result of the long data acquisition times required by both these techniques, respiratory and heart motion generated artefacts led to an unsatisfactory image quality which reduced the power of the method. In an attempt to reduce the respiratory artefacts, a number of authors have applied fast gradient echo techniques in which data acquisition is performed during several consecutive periods of breath-hold of about 20 s. Using such techniques, an improvement in the image quality of venous bypasses was achieved. However, interpretation of the increasingly used IMA bypass grafts, in particular in the proximal region, remains problematic.

A further reduction in the examination times was made possible by introduction of contrast medium-enhanced sequential angiography [8]. The development of high-power
gradient systems has made possible gradient echo sequences with ultrashort repetition and echo times used to perform contrast medium-enhanced MR angiography during a breath-hold period of 20 s. With this technique, the imaging of the IMA bypass grafts over its entire length was decisively improved. However, the lack of the ECG trigger means that assessment of the distal anastomosis remains inadequate [9]. The aim of our study was noninvasive investigation of CABG with different MR techniques and correlation of the results with conventional coronary angiography.

A further objective was to evaluate the Haste sequences with respect to the assessment of distal anastomoses.

2. Patients

In the present study, 25 patients, 5 females and 20 males, with an average age of 62 (52—79) were examined with the Haste-, Navigator- and the Fisp-3-D sequences. All patients were subjected to a routine X-ray coronary angiography in response to recent angina pectoris symptoms. In all patients a noninvasive stress testing such as electrocardiographic or echocardio graphic stress testing or in few patients myocardial scintigraphy were performed due to local clinical guidelines for invasive cardiac procedures. The MRI was performed within one week following invasive procedure. All patients were instructed that participation was voluntary, informed about possible risks, and gave their written consent. The average interval between the bypass surgery and MRI was 7.3 years.

A total of 63 bypass grafts with 78 distal anastomoses were examined, 15 of which were arterial (IMA) and 63 venous (CABG).

In 38 cases, the bypass grafts led into the area supplied by the LAD, 20 into the area supplied by the left circumflex branch (CX) and by the right coronary artery (RCA).

For the assessment of the distal anastomoses, 481 distal anastomoses from 185 patients (mean age 65.3 ± 9.6 years, range 43—81) were the focus of this examination.

2.1. Magnetic resonance imaging

All investigations were performed using a 1.5 Tesla Magnetom Vision device (Siemens AG, Erlangen, Germany), the patients were examined in supine position. Data acquisition was performed using a circularly polarized (phased array) body coil. Initially, a turbo fast-low-angle-shot (Flash) sequence (TR/TE 1100/2.3 ms, field of view 400 mm, flip angle 10°, matrix 128 × 256, slice thickness 8 mm) was obtained in various planes (4 × transversal, 1 × coronary, 1 × sagittal) during a breath-hold in deep inspiration. This images were used as localizers and for the exact planning of the following sequences.

2.2. Haste

The Haste (half Fourier acquired single shot turbo spin echo) measurement was a T2-weighted turbo spin echo sequence in which, after ECG triggering during a breath-hold period of about 20 s, seven slices with an individual slice thickness of 5 mm were acquired (Fig. 2a). The repetition time (TR) and the echo time (TE) were 800 and 43 ms, respectively. The flip angle was 150° and the field of view (FOV) was between 240 and 320 mm. The matrix was 144 × 256. The pixel size was between 0.9 and 1.25 mm depending on the FOV. The coronary vessels appeared as signal-free structures which could be differentiated from the surrounding signal-rich epicardial fatty tissue.

2.3. Navigator

The characteristic feature of the 3D angiography sequence with Navigator echo in which a three-dimensional data set is recorded under conditions of fat suppression and retrospective respiratory gating, is the continuous monitoring of diaphragmatic motion in the free breathing patient.

A spin echo (SE) pulse is used to track the variation of the z-position of the diaphragm during the scans. By triggering on diaphragm motion, a reduction in respiratory-related artefacts is achieved. Data were acquired during a fixed period after every R-wave so that all measurements were performed during the mid-diastolic period. A fat suppression pulse was applied immediately prior to each measurement in order to avoid a superposition of the vessels. TE was 2.7 ms, TR 800 ms, and the FOV was between 240 and 300 mm, the matrix measured 128 × 256. On the basis of these parameters, a pixel size of between 1.8 and 2.3 mm could be achieved. Due to the limited volume size of 48 mm, two overlapping slices had to be recorded to ensure that the course of the graft was completely covered.

Depending on the heart rate, the time required to record a single slice was approximately 7 min, with a total examination time of 45 min on average.

2.4. Fisp-3-D

The Fisp-3-D sequence is a gadolinium-enhanced, T-2 weighted and ECG-gated angiography sequence with an optimized bolus tracking. During a breath-hold period of 25—32 s, 30—34 partitions were acquired. TE was 1.4 ms, TR 4.4 ms, and the FOV was between 240 and 300 mm, the matrix measured 256 × 256.

2.5. Coronary angiography

Invasive coronary angiography was performed by an experienced cardiologist not involved in the study through a femoral approach including selective catheterization of the grafts or graft stumps. All patients underwent the same coronary angiography procedure with the use of a nonionic contrast medium (Ultravist 370, Schering AG, Berlin). At least two orthogonal views were obtained for each graft. Narrowing > 50% of the lumen diameter by visual assessment was defined as a significant stenosis and documented for each bypass vessel. The localization was noted regarding proximal or distal anastomosis or the central bypass section. The details are depicted in Table 1.

2.6. MR data analysis

An experienced cardiologist and radiologist who were blinded to the results of coronary angiography but informed...
about the surgical graft anastomosis evaluated independently all MRIs.

Evaluation was based upon the single-slice images in the sagittal and coronal planes. The bypasses were classified into three different sections:

1. Proximal anastomosis upon the ascending aorta or the origin of the IMA from the subclavian artery for the IMA grafts
2. Main stem of the bypass graft
3. Distal anastomosis: connection to the native coronary artery

Further classification was based on the following categories: patent, stenotic, occluded and not assessable due to poor image quality.

The image quality was rated according to the following scale:

Good: exact assessment of the proximal and distal anastomosis and the bypass course in two orthogonal sections
Fair: exact assessment of the proximal and distal anastomosis and the bypass course in one orthogonal section
Poor: exact assessment of the proximal anastomosis and the bypass course in one orthogonal section

3. Results

3.1. Magnetic resonance imaging

3.1.1. Haste sequence

Of the 47 patent bypass grafts, 44 (94%) were correctly identified; one patent bypass was incorrectly assessed as occluded.

Distal anastomosis was assessed in 43 of the 54 open anastomoses (80%).

The sensitivity and specificity was 94% and 75%, respectively (Table 2).

3.1.2. Navigator sequence

With the Navigator sequence, 35 of the 47 open bypass grafts were diagnosed as patent and two bypass grafts were incorrectly judged to be occluded. Eight bypasses were not assessable as either the image quality was too poor or the vessels were located outside the imaging volume.

Of the 18 occluded bypasses, 14 were correctly identified with four being falsely judged to be patent.

Distal anastomosis was assessed in only 28 of the 76 cases (37%).

The sensitivity and specificity was 74% and 78% (Table 2).

3.1.3. Fisp-3-D sequence

Of the 47 patent bypass grafts, 44 (94%) were correctly identified, two patent grafts were incorrectly assessed as occluded and one occluded graft was assessed as open. The IMA grafts were assessed correctly in 14 of 16 patients.

Distal anastomosis was assessed in 38 of the 54 open anastomoses (70%).

The sensitivity and specificity were 94% and 88%, respectively (Table 2).

3.1.4. Evaluation of the distal anastomosis with the Haste sequence

At the distal anastomosis, 91 of the 113 IMA (80.5%), 65 of the 87 left anterior descending (LAD) (74.7%), 89 of the 112 right coronary artery (RCA) (79.5%), 73 of the 102 posterior lateral artery (PLA) (71.5%), and 49 of the 67 diagonal artery (D1) (73.1%) bypass grafts with fair to good image quality were assessable (Table 3). Grafts with a poor image quality were excluded from the further statistical analysis as the sensitivity in these cases was too low to justify clinical application.

Analysis of the Haste sequences showed a sensitivity of 89.58% and specificity of 98.33% in assessing the patency of coronary bypass vessels. The lowest sensitivity was for distal IMA grafts, followed by the LAD grafts. The highest sensitivity was seen for D1 and RCA grafts. Only the distal PLA segments had a lower specificity of 92.3%. The detailed results are depicted in Table 4.

Where image quality was good, sensitivity and specificity were 93.4% and 98.9%, respectively, whereas the corresponding values were 61.1% and 96.3% for medium image quality and 55.6% and 92.9% for poor image quality.

There were a total of 52 stenoses with luminal narrowing of >70% in the distal area. Of these, 7 of the 8 IMA, 13 of the 15 LAD, 8 of the 10 D1, 9 of 10 RCA, and 8 of the 9 PLA stenoses could be identified. This evaluation included only those...
patients with good or satisfactory image quality, as stenosis assessment in grafts with a poor image quality is impossible.

### 4. Discussion

The results of this study demonstrate that CABG can be investigated noninvasively using MRI. A prerequisite for successful MRI diagnosis of coronary artery bypass grafts is a powerful MR scanner with a gradient strength of at least 25 mT/m and a rise time of 300—600 μs.

This study shows that the patency (Fig. 3) or occlusion (Fig. 1) of a bypass graft was detectable with a sensitivity of 94% for both sequences and with a specificity of 75% for the Haste sequence and 88% for the Fisp-3-D sequence. The Navigator sequence shows a sensitivity and specificity of 74% and 78%, respectively. Distal anastomoses (Fig. 2) were assessed in 80% of the cases with the Haste, 70% with the Fisp-3-D technique, and in 37% of cases with the Navigator sequence. An evaluation of coronary artery bypass graft stenosis is actually not possible due to the low spatial resolution of the method.

In this comparative study, we have demonstrated the ability of noninvasive MRI to identify the distal anastomoses in a group of patients undergoing conventional coronary angiography. Despite the small caliber, mobility during the heart cycle and the tortuosity of the grafts, their patency can be assessed with the Haste technique during a short period of breath-holding (Fig. 2).

The Navigator sequence shows a lower accuracy as the Haste technique in assessing the course of the bypass graft and only about one-third of the distal anastomoses were identified. The lower image quality of the Navigator sequence is due in part to artefacts arising from patient motion during the 12—14 min data acquisition period and also

<table>
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<th>95% CI high</th>
<th>Specificity</th>
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Fig. 1. Fisp-3-D sequence: occluded graft to the RCA.

Fig. 2. (a) Haste sequence of the distal anastomosis of a LAD bypass. (b) Corresponding conventional coronary angiogram to (a).
to the fact that the course of the bypass and the distal anastomoses are located at the edge of the imaging volume. Moreover, calm and regular breathing is mandatory because the dome of the diaphragm then forms a longer plateau at the end of expiration than at the peak of inspiration, thus increasing the efficiency of the retrospective reconstruction algorithm and improving the resolution of the scans. Another limitation of MRI is the requirement of a regular heart rhythm. Irregular heart beat and/or frequent extra systoles result in a degradation of image quality. The same is true for setting a proper trigger delay to acquire images in mid-diastole, in which there is a period of relative diastasis of the heart with both little intracavity blood flow and little cardiac motion, but with a residual coronary blood flow.

The advantage of the Fisp-3-D sequence is the higher diagnostic accuracy and the better image quality of IMA grafts. The ultra short echo and repetition times used in the current Fisp-3-D sequence offer further advantages. Three-dimensional data acquisition could be performed within a single breath-hold, minimizing artefacts from patient movement or independent of flow, because the short echo time practically eliminate flow dephasing. By using the Haste- and the Fisp-3-D sequences we have been able to visualize the course of venous and arterial grafts.

The majority of the clinical results so far have used T1-weighted spin-echo sequences [10] to obtain morphological information. The sensitivity achieved ranged from 73% [11] to 98% and specificity varied from 56% [12] to 85% [13]. The study of Von Smekal et al. [14] shows a sensitivity between 93% and 100%, and a specificity of 86–88% by using gradient and spin-echo sequences.

In the studies performed to date, it has proved difficult to image IMA bypass grafts. The reasons for this are the significantly smaller diameters of 1–3 mm compared to the 3–6 mm of a venous bypass and the imaging artefacts arising from the necessary use of metal clips. There are several studies, in which an evaluation of the IMA graft was not possible due to the image quality [10, 15]. In contrast to these studies, the investigations by Knoll et al. [16] and Wintersberger et al. [17] achieved a sensitivity of 94%. However, it must be taken into account that the data of Gomes and Theissen are from 1987 and 1989, respectively, and were not performed with the powerful gradient systems available nowadays.

There are few studies which examined the detection of graft stenoses with MRI.

The study of Langerak et al. focused only on venous grafts. This study showed a sensitivity and specificity of 65–82% and 82–88% for the detection of a grafts stenosis > 50% and 73% and 80–87% for a grafts stenosis > 70% [18].

In our experience, the best results are available with a spin-echo sequence in breath-hold technique due to the fast data acquisition, the immediate availability of the images, the low susceptibility to metal artefacts and the higher sensitivity in the assessment of the distal graft segments.

Furthermore, the visualization of the stent lumen has been jeopardized by artefacts and did not allow a qualitative assessment of the grafts in this growing patient group.

Since 2000, several studies have shown that subsecond MSCT can be used to successfully visualize bypass grafts several years after surgery.

In a previous study with 182 grafts in 65 patients, a sensitivity of 97% and specificity of 98% were reported [19]. One disadvantage of MRI and MSCT is that only about 90% of the grafts are assessable. In a study by Martuscelli, 87.5% of the grafts could be evaluated in a good image quality. However, these 84 patients showed excellent sensitivity and specificity of 97% and 100%, respectively, as well as diagnostic accuracy of 99% [20].

The sensitivity, specificity, predictive values and accuracy analyzed by graft type were not significantly different between the both methods MSCT and MRI. The sensitivity for the detection of vein graft patency was 100% for MSCT and 92% for MRI and shows no statistical significance [21].

Advantages of MSCT compared with MRI might include the rapid imaging time, the ability to be used in patients with pacemakers or in acute patients with the need of intensive care monitoring. The main advantages of MRI would include the lack of ionizing radiation, fewer adverse events form contrast-enhancing agents and the potential to be carried out in combination with other functional test.

In contrast to MSCT, MRI allows the use of coronary flow reserve measurement to assess the functioning of the bypass grafts and coronary circulation downstream [22]. This offers the possibility of integrating bypass evaluation into a multimodular test protocol along with the determination of global and regional contraction, myocardial perfusion and myocardial reserve, and a vitality assessment.

But, the use of adenosine increases both the duration and the cost of this method.

The factors are mentioned in the next sentence: An MRI examination is only conditionally feasible for patients without atrial fibrillation and tachycardia. Furthermore, extremely agitated or claustrophobic patients cannot be examined.
This study in symptomatic patients after CABG has shown, that MRI could be used for assessing long-term patency and can help for exact timing of interventional procedures. As regards the detection of bypass patency, MRI offers, in combination of different sequences, the possibility of imaging the entire course of the vessel (Fig. 3) and, in 80% of the cases, allows distal anastomoses (Fig. 2) to be visualized. Since around 30% of all patients suffered from angina pectoris in the first year following bypass surgery [23], the assessment of bypass patency in the early postoperative phase represents one area of initial clinical application, since coronary angiography should be avoided during this period and the bypass occlusions are mostly due to complete thrombosis. With indications of this type, it then does not matter that the power of MRI to detect bypass stenoses is still too low. Further possible areas of application are for patients with renal insufficiency, contrast medium allergy, peripheral artery disease or in other cases in which coronary angiography is contraindicated.

Patients with multivessel disease generally do not become symptomatic until several bypasses are occluded. As MRI enables the definitive determination of occluded bypass grafts, this is the imaging procedure of choice for the follow-up of asymptomatic patients, especially since after five years, nearly every third patient has an asymptomatic bypass occlusion.

A further group consists of patients with atypical thoracic symptoms following CABG surgery. An invasive procedure can often be avoided, in particular for elderly patients, if an occluded bypass can be ruled out by noninvasive MRI. However, primary invasive techniques should still be used for patients with definite chest pain or ischemia.

At its present state of development, MRI is not able to replace selective coronary angiography, but provides a new approach to the evaluation of CABG patency. In addition, this new technology holds promise for allowing noninvasive detection and characterization of CAD in a selected patient group as a screening procedure.

The technique requires further improvements of spatial resolution so that the coronary artery bed beyond the anastomosis can be detected. Our finding confirms previous studies that MRI allows differentiation between patent and occluded grafts. However, the novel finding in the present study is that high-resolution MRI enables the assessment of the distal graft segments and the anastomoses with a fair diagnostic accuracy. This offers perspective for noninvasive screening of patients who present with chest pain after bypass surgery.

References

Appendix A. Conference discussion

**Dr J. Hartman (Rotterdam, The Netherlands):** I have no question, but I want to make one remark.

In one of your first slides you showed that within 10 years, 50% of the bypasses are occluded. I hope that’s not true.

**Dr Wittlinger:** The occlusion rate of venous grafts is about 50% after 10 years, the occlusion rate of the IMA grafts is about 15%. I think these data are correct and are confirmed by several invasive follow-up studies after CABG surgery.

**Dr J. Roquette (Lisbon, Portugal):** Did you compare this MRI technique with a CT scan 64?

**Dr Wittlinger:** Yes, we did. The new MSCT scanner, especially the 64-slice generation, has a very good image quality, but there is a need of about 150 ml contrast agent. In patients with renal failure, I think, MRI is better for imaging the coronary bypass grafts.

I believe that, in future, MSCT will be the best method for imaging coronary arteries and grafts, and it will the best method of choice for the analysis of functional parameters.

But there is the need of contrast agent and about the double radiation dose compared with conventional coronary angiography.